GaSb photovoltaic cells ready for space and the home

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Gallium antimonide is receiving a good deal of interest for photovoltaic applications, with its key advantage being its long wavelength infrared response. The GaSb cell was originally developed as a concentrator booster-cell in a GaAs/GaSb tandem stack, while more recently GaSb cells have been used as thermo-photovoltaic (TPV) cells enabling the generation of electricity in home furnaces.

The III-V material system offers a large variety of well-behaved materials for engineers to work with. This variety offers material properties that are superior to those of silicon for many specific applications. Thus, the higher electron mobility for GaAs has led to the use of MESFET circuits for very high frequency applications, while the direct bandgap transitions associated with many of the III-Vs have led to many successful photonic devices, such as LEDs and diode lasers. Epitaxial III-V film deposition technologies bring additional variety and enable many device applications, including HEMT, HBTs and visible LEDs.

Unfortunately, there is also often a penalty with III-Vs associated with process complexity. Ternary and quaternary compounds are more difficult to work with than silicon. Epitaxy generally entails the use of ultra-high vacuum or large quantities of poisonous gases, while crystal growth can require high-pressure systems. Finally, silicon has a passivating oxide whereas GaAs devices often require epitaxially grown AlGaAs layers for surface passivation.

We have been fortunate to find a III-V device where there are not only applications that are inaccessible to silicon, but where the material and device processes are simple analogues to silicon processes. This device is a GaSb photovoltaic cell. The advantage of GaSb compared with silicon or GaAs for such an application is that it responds to longer wavelength infrared radiation. GaSb is a direct bandgap material with infrared absorption extending out to 1.8 μm. The first GaSb cells were made in 1989 by the present authors, then at Boeing. These cells were used in combination with transparent GaAs cells as mechanically stacked tandem GaAs/GaSb cells for use on space satellite solar power arrays. In this configuration, the GaSb cell using the sun's spectrum between 0.9 and 1.8 μm (see Figure 1) added 7 percentage points to the 24% GaAs cell to establish a new world record of 31% for space cell conversion efficiency[1].

In 1993, the present authors left Boeing with an exclusive license to the GaSb cell technology and joined JX Crystals Inc. JX Crystals had been supplying GaSb wafers and realized that the GaSb cell would enable thermophotovoltaic (TPV) applications[2]. Figure 2 shows the reason why GaSb is attractive for TPV. While the sun is very hot with a blackbody temperature of 6000 K, man-made combustion sources are not nearly as hot. A ceramic element in a flame might operate at approximately 1700 K. At this temperature, the peak power wavelength for the blackbody spectrum has shifted from 0.5 μm for the sun's spectrum to 1.8 μm, a value well matched to the GaSb cell response band edge.

So, the GaSb photovoltaic cell has unique and exciting applications. In addition, we have found that its processing is very analogous to simple silicon solar cell processing. For example, since the vapour pressure of antimony is lower than that of As or P, we are able to use converted silicon CZ pullers for crystal growth. Furthermore, we can form pn junctions by simple Zn diffusions without Sb overpressure. These and other process advantages (e.g. no epitaxy, no polish, cast polycrystalline ingots) promise to make GaSb photovoltaic cells inexpensive in high volume production.

High power density

In 1992, the Boeing team fabricated a photovoltaic advanced space

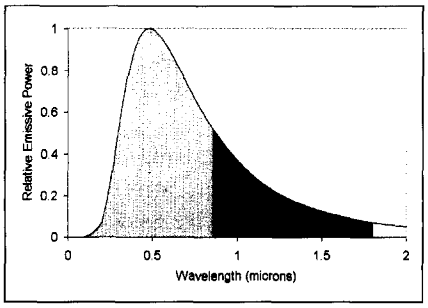

Figure 1. The sun's power spectrum is represented by a 6000 K blackbody. The GaAs response band is shown in yellow and the GaSb response band in red. The tandem GaAs/GaSb cell holds the world record for space solar energy conversion efficiency at 31%.

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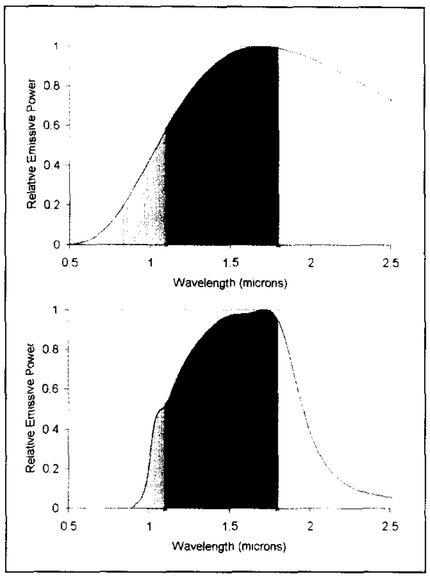

Figure 2. (a) The power spectrum for a 1700 K blackbody. The small yellow region shows the response band for an Si solar cell. A GaSb TPV cell converts energy in both the red and yellow bands to electric power. (b) The 1700 K spectrum seen through a simple dielectric filter deposited on the TPV cell. The longer wavelength energy can be reflected back to the emitter for improved system conversion efficiency.

power (PASP) module incorporating an array of GaAs/GaSb stacked tandem cells. This module went up into space in 1994 into a high radiation orbit. Besides the innovative GaSb infrared booster cell, this PASP module used an array of fresnel lenses for the first time to concentrate the sunlight onto the cells (Figure 3). This allowed small cells 1 cm^2 in diameter and 0.5 mm thick to produce approximately 1 W each, as opposed to the traditional flat plat approach where large 2 x 4 cm^2 cells have to be thinned to 0.1 mm thickness in order to produce the required lightweight array. This innovative concentrator PASP module allowed higher power per unit area as well as higher power per unit mass than the traditional flat plat array. Because the cell area was small compared to the lens area, a thick cover slide could be used to shield the cells from radiation damage without a major weight penalty. NASA has reported that this PASP array has the lowest radiation degradation rate of all the other modules that have flown[3]. Furthermore, the cell cover can be shaped to relax the concentrator pointing accuracy requirement to ±4°. Hence, the PASP module had absolutely no problems tracking the sun. As a result of this pioneering concentrator module, a 2.5 kW concentrator power array using fresnel lenses and tandem cells is being successfully used to power the Deep Space I satellite.

From the III-V process engineer's point of view, the salient advantage of concentrators in space is that small simple devices can operate at high power densities. It is obviously more cost effective to make 1 cm^2 devices on standard thickness wafers that operate at 1 $W.cm^{-2}$ than to make large thin devices that operate at 20 $mW.cm^{-2}$. It is also noteworthy that higher power densities lead to higher efficiencies. The early GaAs/GaSb tandem cell record of 31% was recorded at 100 suns concentration. Recently, JX Crystals and Tecstar have worked together to combine a Tecstar InGaP/GaAs concentrator cell with a JX Crystals GaSb concentrator cell to form a stacked cell. Operating at 15 suns, the GaSb cell boosted the Tecstar cell efficiency by 6.3% from 23.3% to 29.6% for the resultant InGaP/GaAs/GaSb stacked cell.

The idea of using solar cells to generate electricity from man-made heat sources is not new[4]. Until the GaSb cell was demonstrated in 1989, however, there was no cell that responded in the required infrared range. We were initially intrigued by the possibility of using GaSb for TPV systems. Our curiosity turned to excitement in 1993 when we calculated the electric power densities produced by GaSb cells in TPV systems.

Because the man-made 'sun' is only inches away from the cells in TPV systems rather than 150 million km away, we calculated that power densities in the 2 to 4 $W.cm^{-2}$ range were readily achievable. In 1994, we built our first TPV fuel fired generator and demonstrated a

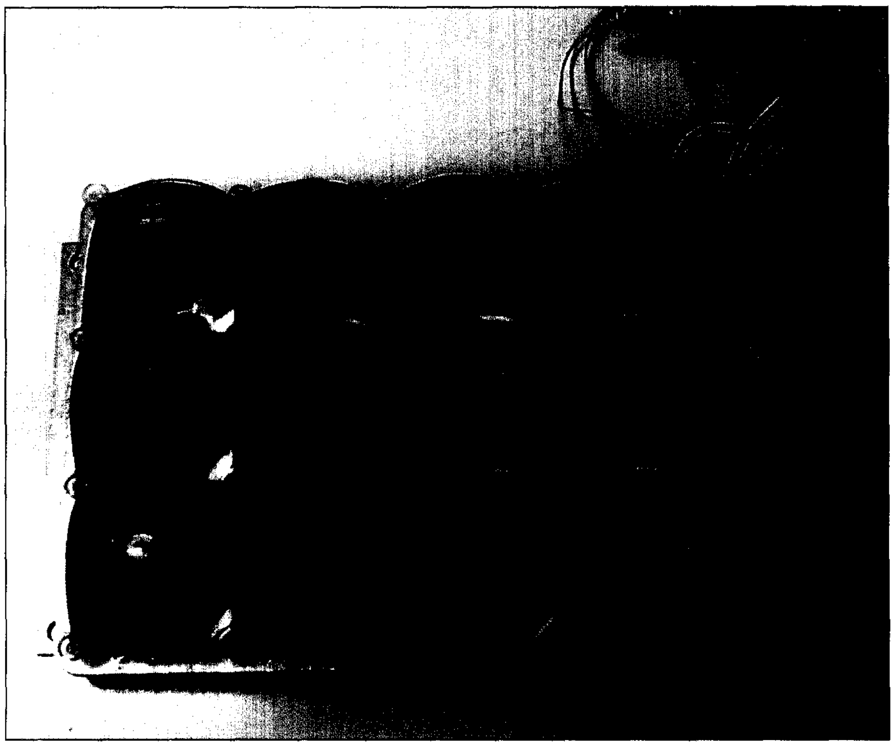

Figure 3. This photovoltaic advanced space power (PASP) module is now in orbit. It uses a 3x4 array of mini-dome fresnel lenses to focus sunlight onto an array of 12 GaAs/GaSb tandem cells. This module performed well and proved the viability of concentrator tandem cells in space leading to the 2.5 kW concentrator array now powering the Deep Space 1 mission.

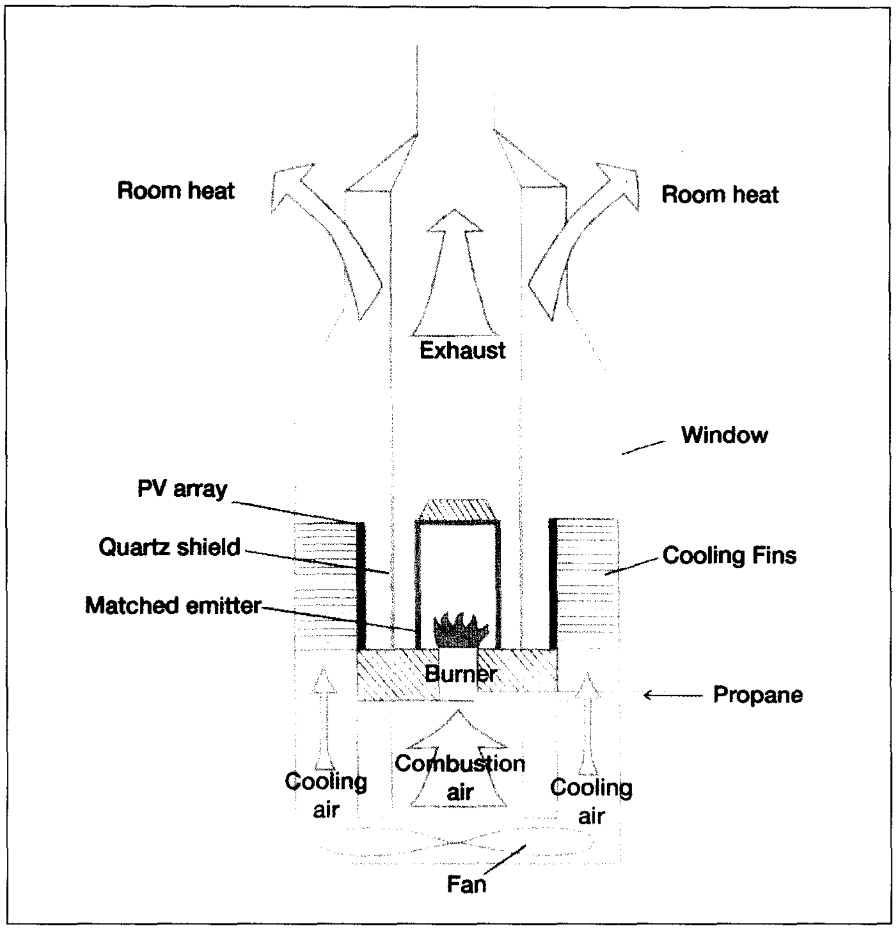

Figure 4. In the prototypical thermophotovoltaic (TPV) generator shown here, a fuel is burned to heat a ceramic element. The glowing ceramic element emits infrared radiation that is converted to electric power by GaSb infrared-sensitive photovoltaic cells. The addition of photovoltaic panels in heating appliances allows electric power to be quietly generated along with the heat. These TPV systems effectively utilize 90% of the energy in the fuel.

power density of 1.6 $W.cm^{-2}$ using a GaSb cell array[2]. More recently, we have demonstrated a TPV generator[5] with cells operating at 2.5 $W.cm^{-2}$.

Figure 4 shows the basic TPV concept. In a TPV unit, a fuel such as propane or methane is burned in a heater or furnace and a ceramic element is located in the flame. The ceramic element emits intense infrared radiation and a photovoltaic array surrounding this emitter converts this infrared energy into electric power. Thus, a TPV unit co-generates heat and electricity. Over the past several years, we have demonstrated that GaSb cells enable a large number of TPV applications ranging from a battery charger for the Army (Figure 5) to a home heating-stove (Figure 6) to an electric vehicle.

The fact that TPV systems are quiet has led us to our present customer base. Our first customer has been the US Army. Since the soldier of the 21st century will use a lot of electronics, the Army is supporting the development of a quiet battery charger that can use common logistic fuels. This will enable them to switch from throwaway batteries to rechargeable batteries.

Our second set of customers has proven to be solar PV module distributors and users. TPV systems have many of the same attractive features as solar modules. Both systems are quiet, clean, efficient and modular. Furthermore, TPV units both extend the potential market for photovoltaics and make traditional solar PV more appealing. TPV technology is geographically complementary with solar photovoltaics in that solar works well in sunny climates and TPV works well in colder climates. It is also seasonally complementary in that solar panels can supply electricity during the sunny summer months and TPV can supply heat and electricity during the cold and cloudy winter months.

JX Crystals has developed the small TPV heating stove[6] shown in Figure 6 for the off-grid solar market. Families that live away from the electric power grid who have solar panels and batteries can purchase a TPV heating stove to keep themselves warm and keep their batteries charged in winter months. Our TPV unit can be used as a fireplace insert or as a vented stove located in the corner of the family room. It generates approximately 25 000 BTU per hour of heat and 100 W of electricity for battery charging. A soft, warm glow is visible through the front window of the 'Midnight Sun®, TPV stove.

Low cost processing

JX Crystals sees TPV penetrating three progressively larger commercial markets over the next decade. The first market is the off-grid market where solar panels are now widely used. This includes cabin, boat, remote site and military applications. The second market is the grid connected self-powered furnace market where the TPV electricity is used to operate the furnace electric auxiliaries such as the air blower or water pump so that the furnace is able to operate during power outages. The third market is the home co-generation market where the TPV furnace supplies heat and most of the electricity for the home with the electric grid serving as a backup system.

In the next century, TPV holds the promise of tremendous fuel-efficiency by co-generating electricity in otherwise traditional furnaces at a reasonable cost. Heating fuel is

Figure 5. In this 1 kW cylindrical TPV generator design, twenty GaSb converter circuits surround a glowing infrared emitter. Each circuit generates 50 W. In this photograph, several of the circuits have been removed in order to show the glowing emitter. A variation on this design can be used for an outdoor battery charger. A two-cylinder TPV unit can be incorporated in a 2 kW home co-generation furnace.

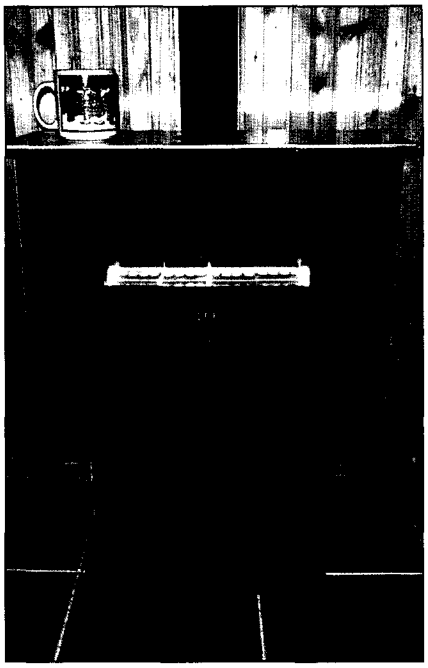

Figure 6. This 'Midnight Sun®' stove burns propane or natural gas to generate 100 W of electricity along with 25 000 BTU per hour of heat. It uses two 2"x10" GaSb panels with each panel generating 50 W.

converted to heat energy at 80 to 90% efficiency in homes, and TPV units can convert fuel to heat and electricity combined at levels at least as high. By comparison, electricity generated at a central power plant and delivered to homes by transmission and distribution lines will often have a dismally low 30% fuel utilization efficiency.

So, a furnace in your garage will be capable of supplying heat and electricity for your house, but is this economically feasible using GaSb TPV cells? If we can make GaSb cells for US$2 per cm^2 that generate 2 $W.cm^{-2}$, then the answer is yes. Then a 1 kW panel in your furnace would cost $1000. Given that you pay $2000 for a furnace now, you could buy a TPV furnace for $3000. It would co-generate heat and electricity with 90% efficiency. Approximately 3 million new furnaces are sold each year in the USA. Assume 1 million become TPV furnaces. This is 1 GW per year of new capacity and a $3 billion annual market.

How can we make GaSb cells at $2 per cm^2? Recent reports[7] have estimated that MESFETs can be made at $5.$cm^{-2}$. This is with a sub-micron ten mask level process. The GaSb cell process is a three mask level process with 10 μm lines. Furthermore, we have demonstrated[6] that we can use cast polycrystalline ingots to make good GaSb cells (published in 1998 and verified by the National Renewable Energy Laboratory). The cost of Ga and Sb in a cell is 10 cents per cm^2.

While the above scenario is exciting, at present it is just a dream. The catch is that high volume production will be required. The MESFET cost projection[7] above assumed thousands of 6" GaAs wafer starts per week. Presently, we are only processing hundreds of GaSb 3" wafers per month. Hopefully someday, our dream will become a reality.

Acknowledgement

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References

[1] J. Avery *et al.*, *21st IEEE Photovoltaic Specialist Conf.* (1990), p. 1277.
[2] L. Fraas *et al.*, *1st World Conf. on Photovoltaic Energy Conversion* (1994), p. 1713.
[3] H. Curtis *et al.*, *1st World Conf. on Photovoltaic Energy Conversion* (1994), p. 2169.
[4] G. Guazoni, *Applied Spectroscopy* 26, NOI (1972), p. 60.
[5] L. Fraas *et al.*, *4th NREL Thermophotovoltaic Conf.*, AIP 460 (1998), p. 371.
[6] L. Fraas *et al.*, *4th NREL Thermophotovoltaic Conf.*, (1998), p. 480.
[7] M. Meyer, *Compound Semiconductor* (March 1999), p. 34.

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